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Calibration of the SNS Eddy Current Scanner for the Quality Control of the Niobium Blanks for Fermilab's SRF Cavities

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1 INTRODUCTION

As part of its effort to fabricate bulk niobium (Nb) SRF cavities for a future linear collider, Fermilab is developing the infrastructure and expertise to provide the scanning of the precursor discs for the SRF cavities for defects and inclusions. The precursor material for high performance SRF cavities needs to be of high purity (0.9999%) and void of foreign inclusions or mechanical defects. Normal conducting inclusions such as tantalum (Ta) clusters larger than ~10-100 µm can cause premature thermal breakdown of the superconductivity in the cavities. We recently commissioned an eddy current scanner for cavity pre-cursor sheets (Figure 1 and Figure 2), on loan from SNS[1]. The SNS scanner was fabricated by FER-PA/Germany on the basis of a design developed by DESY and the German Federal Institute for Material Testing (BAM) [1]. The development consisted in pushing the sensitivity of commercial eddy current systems by an order of magnitude, such as to allow detection of 0.1mm size defects. The scanner uses a turntable system that rotates the Nb sheet under an eddy-current probe that is driven by a commercial eddy current measurement system (Rohmann's Elotest). The probe is made of two coils (the coil diameter is ~3.5 mm), operating in the absolute scheme at ~200 kHz (a second channel, which is typically used at ~1 MHz, is also available). The penetration depth in Nb at 200 kHz is ~0.35 mm. To compensate for disc thickness variations, the probe is levitated above the specimen using a flow of compressed air emitted by the probe itself. During the initial setup of the SNS scanner some possibilities for hardware improvement were recognized and implemented. The most important among them is the installation of a vertical micrometer slide (Figure 2) that allows for better alignment and minimization of the distance between the eddy current probe and the sample. Besides the excitation frequency, the distance between the probe and the sample is the overriding parameter for the resolution of the scanner. We also installed an air-buffer system to dampen pressure variations in the compressed air supply. A more thorough description of the scanner can be found in [2].

Figure 1: SNS eddy current scanner at Fermilab. 1) turntable with sample, 2) eddy-current tester, 3) main-power switch, 4) air receiver.

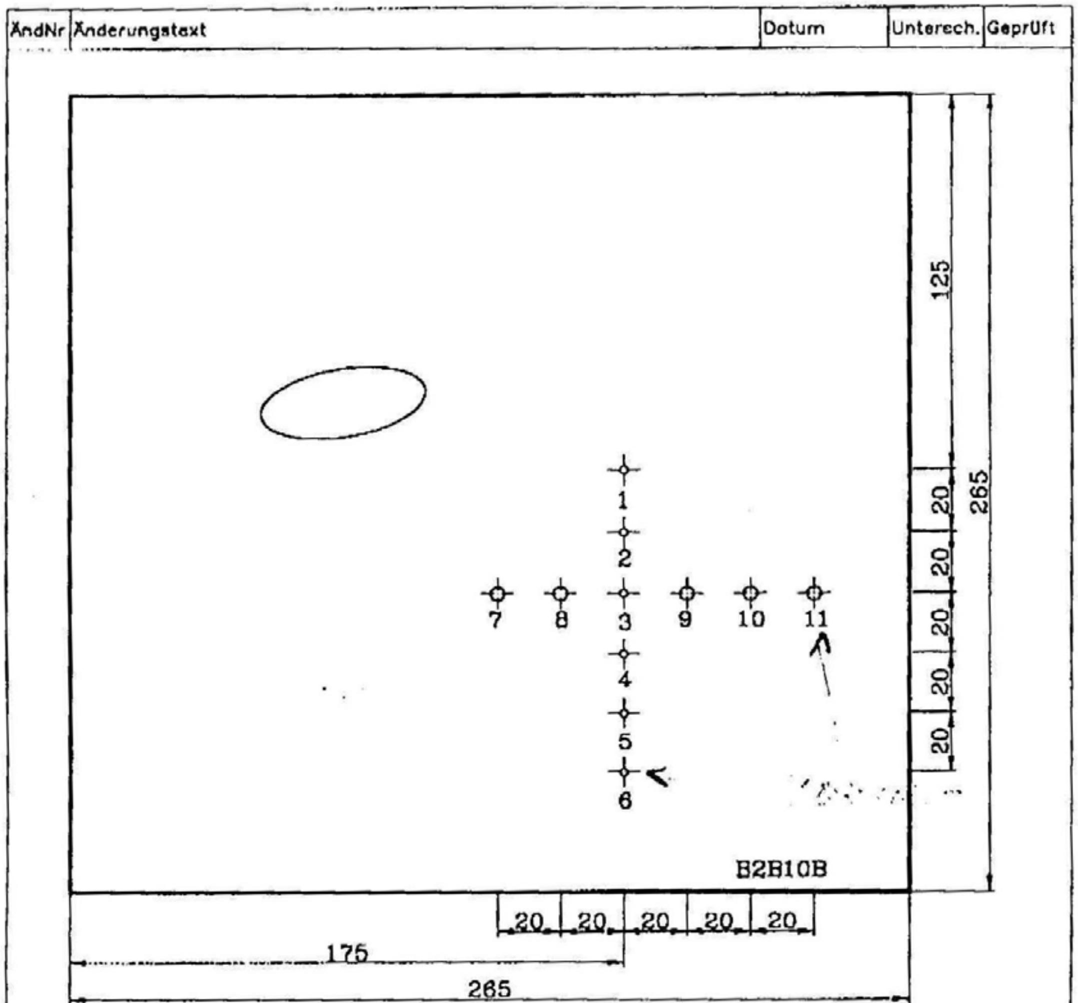
[1] Generously provided to Fermilab by Dr. N. Holtkamp and Dr. D. Stout from the SNS laboratory at Oak Ridge.

Figure 2: Left: Sample-holder with disc for the Fermilab 3rd harmonic cavity and eddy-current probe. Right: Eddy current probe with micrometer slide, compressed air supply tube and signal cable.

The following discusses recent measurements that were performed to quantify the sensitivity of the measurement system using a so-called calibration disc. The calibration disc was manufactured at DESY and contained implanted sub-surface defects of known size and type. A significant number of scans was performed on the calibration disc in the attempt to further improve the understanding of the effect of various parameters on the scanner sensitivity. This note reports on the results of this effort. The DESY calibration disc is described next.

2 DESY CALIBRATION SHEET

The DESY calibration disc is a ~0.1” thick, ~10” square niobium sheet supplied by the Wah-Chang company. It contains eleven implanted sub-surface defects. Figure 3 shows where the defects are located. Most defects are drilled holes of varying diameter, stuffed with Ta powder. The Ta was subsequently melted and the holes closed by superficial e-beam welding in vacuum. Holes 6 and 11 were not filled. The diameter of the holes varies between 120 and 230 μm. The drilling depths vary between 80 and 500 μm. The exact diameter and depth parameters for each hole are listed in Figure 3. Following the preparation of the implants the sheet was chemically polished. Although many scratches are visible on the surface as a result of extensive handling and scanning, no trace of the implants is visible even under a magnifying glass. A defective roller, however, left a visible imprint on the disc, which also generates a strong eddy current response (as a result of the disc height variation). This “defect” is also marked in Figure 3.



Fehler	Sackloch ø[mm]	t[mm]	V[mm³]	mit Tantal gefüllt
1	0,12	0,078	0,0009	Ja
2	0,14	0,21	0,0032	Ja
3	0,145	0,298	0,0049	Ja
4	0,145	0,376	0,0062	Ja
5	0,15	0,474	0,0084	Ja
6	0,15	0,469	0,0083	Nein
7	0,22	0,234	0,0089	Ja
8	0,23	0,333	0,0127	Ja
9	0,22	0,435	0,0165	Ja
10	0,22	0,495	0,0188	Ja
11	0,22	0,501	0,0190	Nein

$V\,[mm^3]$
$1{,}22 \times 10^{-4}$

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BAM LaborVIII.43

Testkörper DESY

Figure 3: Datasheet for the DESY calibration sheet.

3 TEST RESULTS

3.1) Benchmarking with DESY

Scan 18 of the DESY calibration disc obtained with the SNS scanner at Fermilab is shown in **Figure 4** (left) together with a similar scan of the same disc performed at DESY (right). The parameters of the Fermilab (DESY) scan were: 190(170)kHz and 46/66(44/66)dB x/y gain, phase 205(357)°, 170(98) rpm and 2(1.3-1.5)bar probe-pressure. The number of measurement points per track was 1600(3600) and 50(200)μm track spacing. Therefore the total number of points per plot is more or less the same in both scans and the scanner setting comparable. Although this comparison generally reveals that both scanners have similar resolving power, the DESY scanner seems to be capable of bringing out the defects with slightly more clarity. We believe that this is the result of a less favorable signal to noise ratio in the Fermilab case. This issue will be discussed in further detail in the following. First, however, different studies were conducted to further optimize the Fermilab scanner performance. The results of the studies are discussed next.

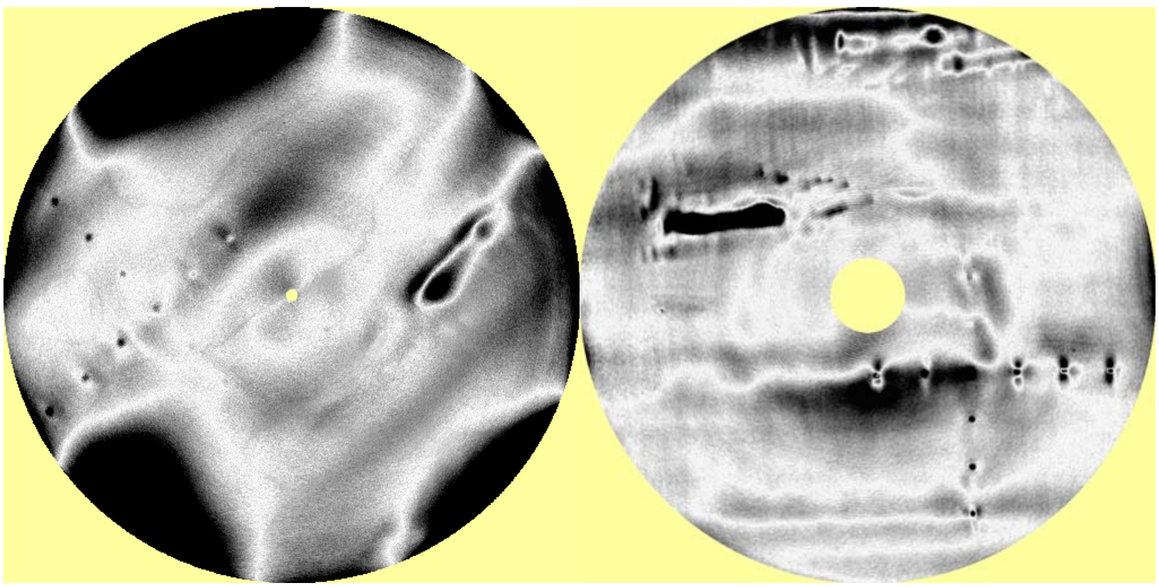


Figure 4: Calibration disc scan obtained with the SNS scanner at Fermilab (scan 18, left) and at DESY (right).

3.2) Variation of the Turntable Velocity

A possible source of measurement noise is mechanical vibration, which produces the same signal as probe to sample distance variations. As mentioned before probe to sample distance is the parameter most affecting the eddy current scan. The SNS scanner was designed for the scanning of very large sheets for the low frequency SNS cavities. Therefore a fast spinning scanner design was chosen, with 170 rpm (to be compared to the ~100 rpm of the DESY scanner). Linear collider type cavities, such as those of interest for Fermilab, are much smaller and the rotational velocity of the scanner can therefore be reduced without increasing significantly the measurement time. A reduction of gear ratio by 60% was obtained by replacing the pulley that drives the belt and turntable (see drawing in appendix A). The turntable rotational speed was reduced accordingly from 170 rpm to 105 rpm. As shown in

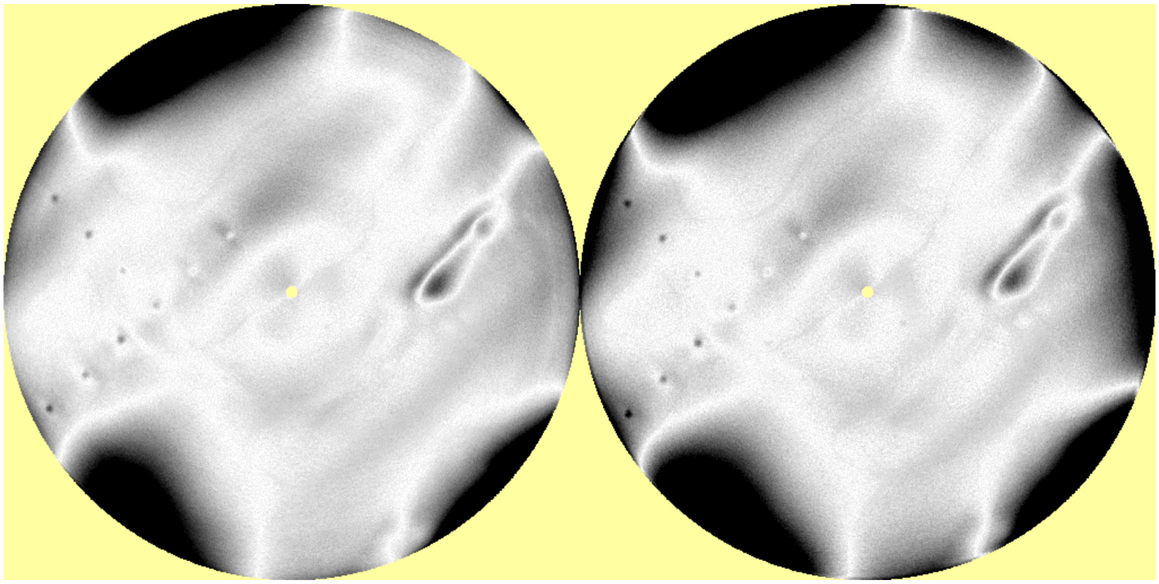


Figure 5: Calibration disc scan obtained with the SNS scanner at Fermilab at 170 rpm (scan 18, left) and 105 rpm (scan 19, right).

Figure 5 comparative measurements do not reveal any significant improvement after reducing the turntable velocity. The measurement data shown in the figure have been obtained at 190 kHz with minimal probe distance, 2 bar probe air-pressure and 1600 points/track, 50 μm track spacing. The new setup will nevertheless stay in place.

3.3) Variation of Probe Air-Pressure

The ECS uses a pneumatic probe distance regulation, whereby the disc is levitated on an air cushion formed between probe and sample by the flow of pressurized air emitted by the probe. Since the probe is spring-mounted a fixed probe to sample distance is imposed by the equilibrium between the pneumatic and spring forces and variations in disc thickness, for example, are compensated. The nominal probe air-pressure setting is ~2 bar. In this measurement the air pressure was varied from ~1.6 bar to ~2.2 bar to explore the effect of the pneumatic distance regulation on the measurement noise level and resolution. Since the variation in probe pressure also determines how much the probe is pushed outside the probe-holder, the probe distance needed to be re-adjusted for each measurement. This procedure involves subjective judgment about what the minimum achievable is on the part of the operator and is therefore not reproducible. Differences in the quality of the scans shown in the following can therefore also partially be the result of varying probe to sample distance settings. As much as possible standardized procedures were used for the probe alignment. The measurements, shown in **Figure 6**, were all performed with 1600 pts/track, 200 μm track-spacing and at 105 rpm.

This comparison indicates that the 1.6 bar pressure measurements produced less signal, while all other measurements produced more or less a similar result. We therefore conclude that the pressure effect is not discernible as long as it is above ~1.8 bar.

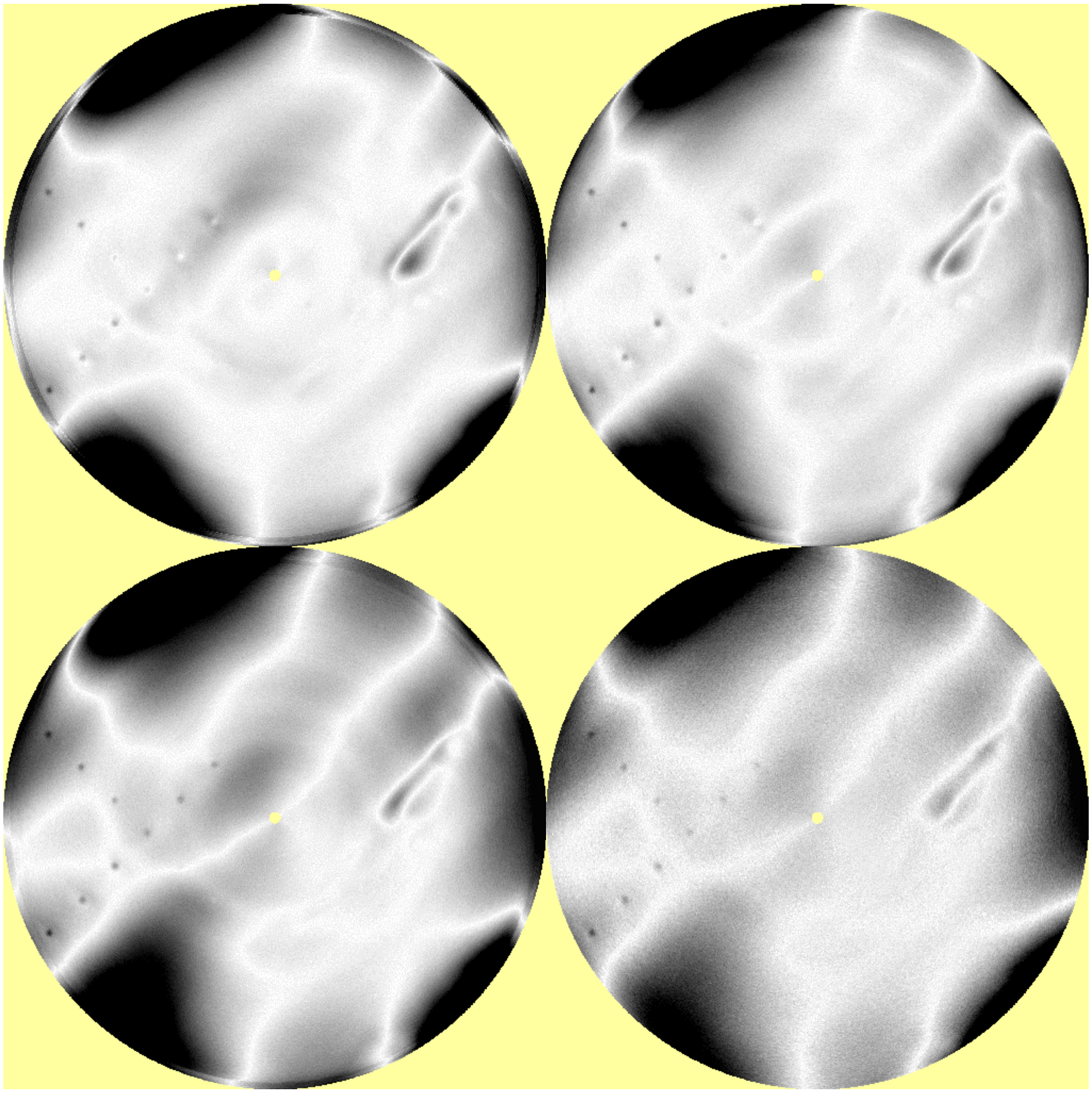


Figure 6: Calibration disc scan obtained with the SNS scanner at Fermilab at ~1.6 bar (scan 28, upper left), ~1.8 bar (scan 29, upper right), ~2 bar (nominal, scan 23, lower left) and 2.2 bar (scan 31, lower right).

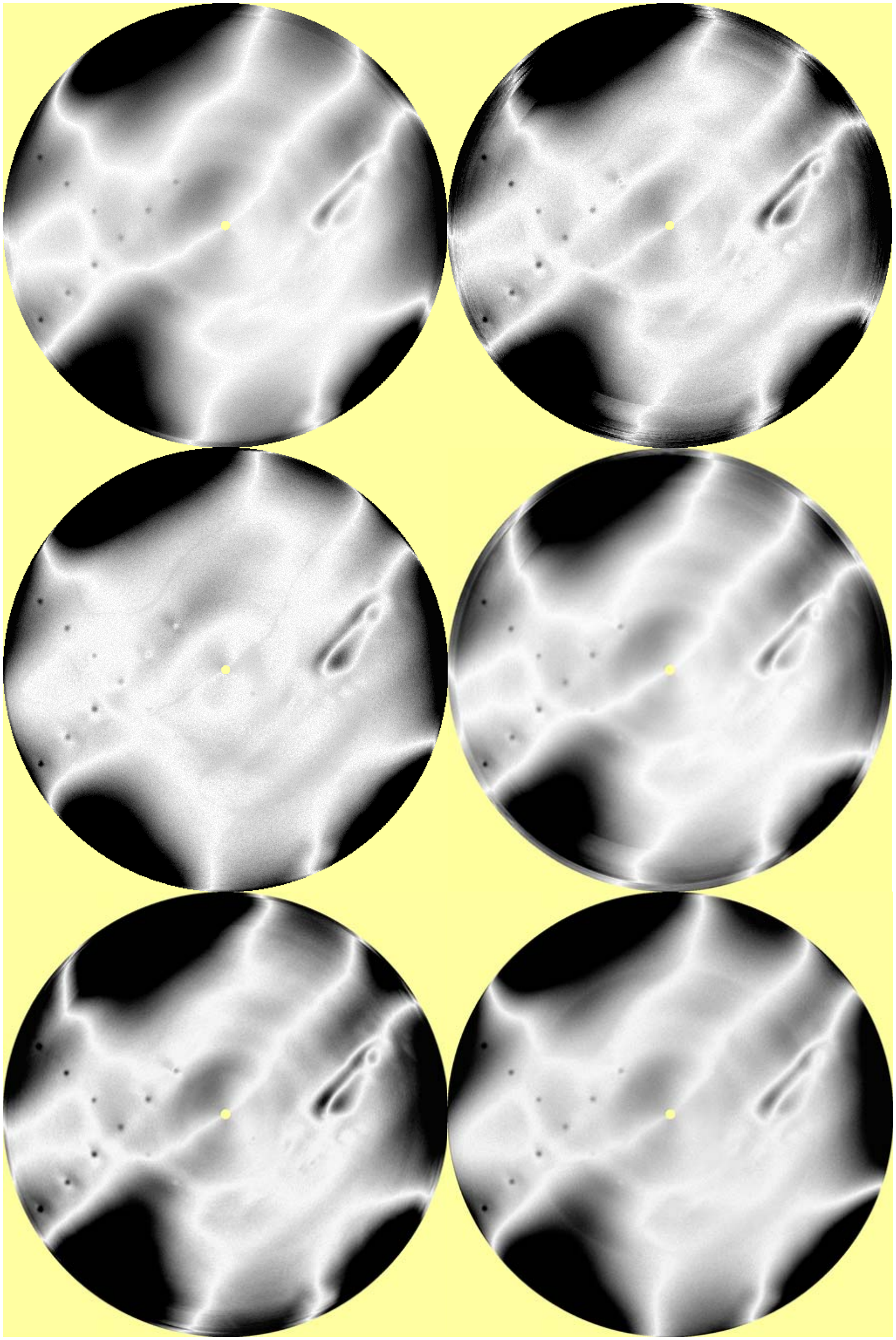
3.4) Variation of Number of Measurement Points

Two very important parameters that can be set in the Niobscan software are the number of points per track (via the angular increment) and the track spacing. The number of points per track is not varied as the head moves further to the center of the rotation. The smallest angular increment that can be set is 0.075°. This corresponds to 4800 points per track. The outer radius of the calibration sheet scan is typically 100 mm. Therefore the spatial resolution (on the circumference) is several microns on the inner edge and ~100 microns along the outer edge of the scan. (The compression of the data toward the inside of the scan of the sheet can be prevented when using the polar plot.) The smallest track-distance that can be set is 50 microns. When working in the highest number of measurement points mode the scanner produces more spatial resolution than can be resolved on a computer monitor (~200 microns when the entire sample area is displayed on the screen) or by a printer (~50 microns at 500 dpi). Averaging of the eddy current therefore takes place when the scanner results of the inner region of the sample is displayed on a computer screen or printed.

It is important to note, however, that the scanner is specified to detect 100 microns size sub-surface defects. The experience with the measurements shown in this report is that defects appear approximately ten times larger in the eddy current scans because their influence is felt by the eddy current probe at distances that are several times the defect size. Therefore, the minimum defect size in the scan is ~1 mm, sufficiently large to survive signal averaging over 100 micron size areas. The problem of loss of information due to the limitations of the representation technology could, however, affect us if we would aim at a resolution of defects that are 10 micron or less in size.

As explained above the eddy current scanner can easily produce more measurement points than can be displayed on a typical computer monitor or printed. Therefore the issue of the number of measurement points is mostly one of measurement time. In the highest number of points settings the scan of the calibration sheet takes ~1 hour. For the given sheet size this is 2-3 times too long for series scans of sheets for a cavity production. The scan data-file is 100 Mbyte in this case, causing further problems for the data handling. It is therefore of interest to to reduce the number of measurement points. The following measurement series aimed at exploring the scanner sensitivity when varying the number of points. Figure 7 shows the results obtained on the calibration sheet varying the number of points per track from 1600 to 4800 and varying the track spacing from 50 μm to 200 μm. The total file size from top left to bottom right is: 7.1 Mb, 14.3 Mb, 28.5 Mb, 21.4 Mb, 42.8 Mb, 85.5 Mb.

Figure 7: Comparison of scans of the DESY calibration disc with varying number of measurement points, ordered from least to most. Top left: 1600 pts/track - 200 μm track-spacing (scan 23), Top right: 1600 pts/track - 100 μm track-spacing (scan 25), Middle left: 1600 pts/track - 50 μm track-spacing (scan 19), Middle right: 4800 pts/track – 200 μm track-spacing (scan 27), Bottom left: 4800 pts/track - 100 μm track-spacing (scan 26). Bottom right: 4800 pts/track – 50 μm track-spacing (scan 32). All measurements were obtained at ~2 bar probe pressure with 105 rpm.



3.5) Filtering

Filtering has been brought forward as a way to improve the SNS scanner resolution. The NiobScan software (developed by R. Cassperson/BAM) is used for both DAQ and data analysis and uses a binary file (.NSD) to store the data. C. Boffo developed a Matlab™ based program that reads the data in the binary file and filters them. The filter is a default Matlab™-type band-pass FIR filter. A special, simple interface for the operator was also created. It essentially removes the low and high frequency "noise" and keeps the signals related to the defects. The filtering can take a long time if the number of points is set to the maximum possible. With a 100 μm track distance and 4800 pts/track, however, the filtering time for a 3rd harmonic cavity disk is estimated to be 3 minutes. The filter algorithm is described in detail elsewhere [3]. **Figure 8** and **Figure 9** show how powerful this simple filtering routine is. Especially when represented in the Matlab™ editor the defects of the calibration sheet are nicely resolved. **Figure 9** also shows how the filtered image appears when reconverted into NiobScan.

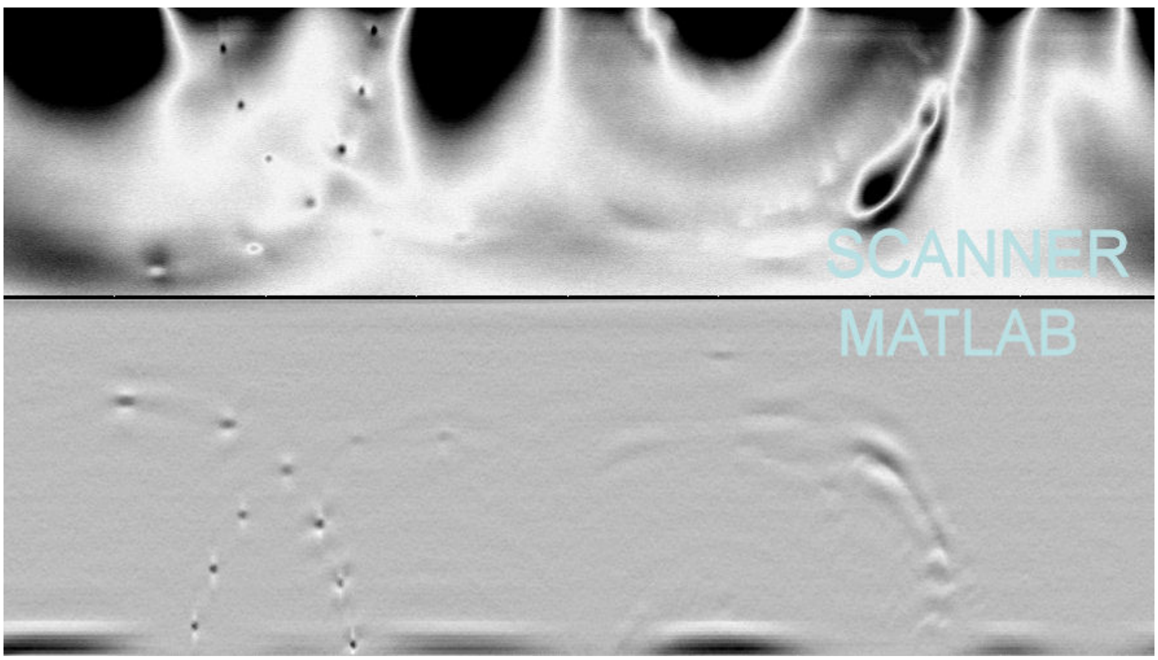


Figure 8: Comparison of original (scan #18) and filtered (w. Matlab) scans of the DESY calibration disc. The results are shown in the ϕ(lines)/r(columns) mode.

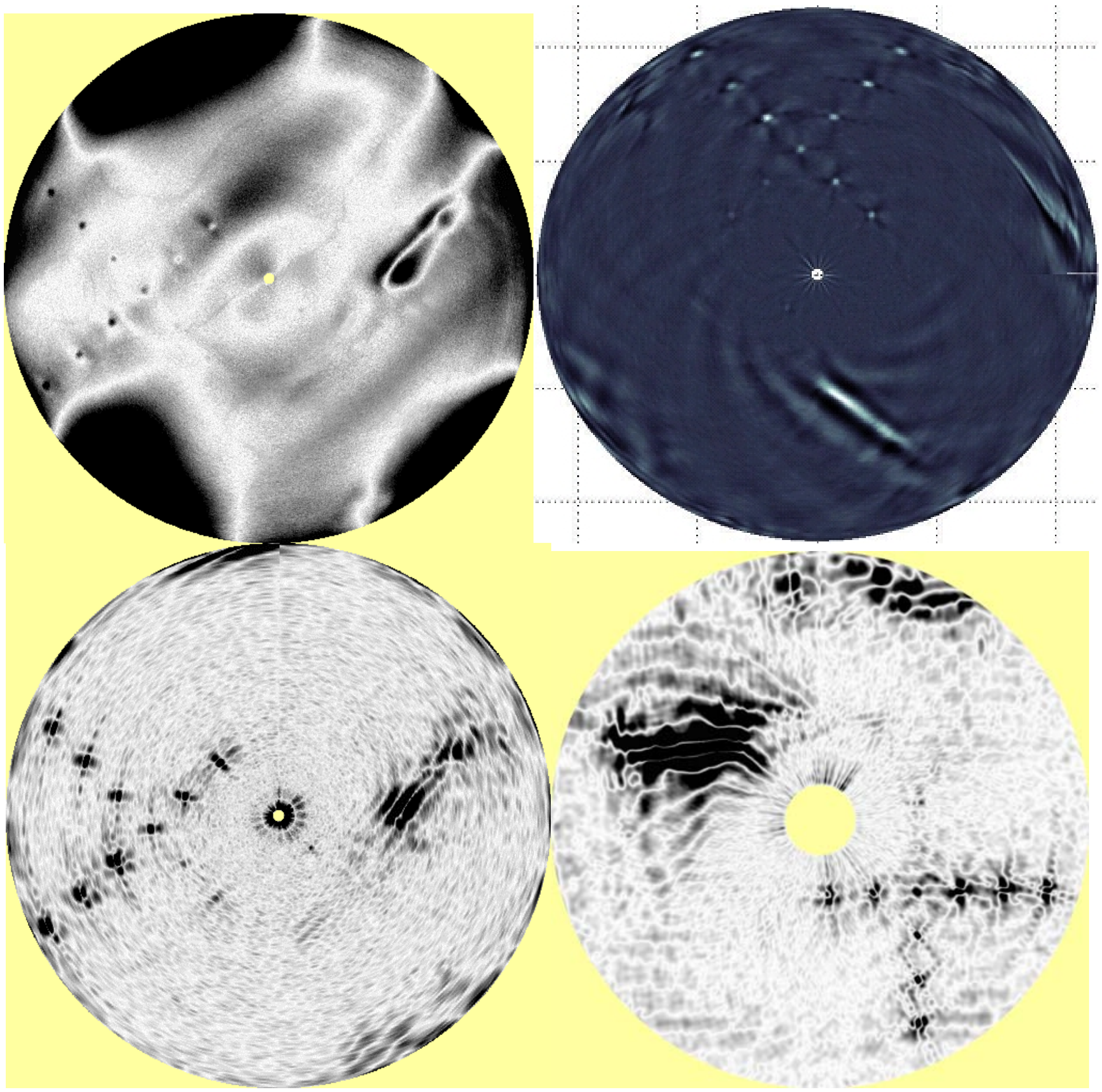


Figure 9: Eddy current scans of DESY calibration sheet: Top left: FNAL scan before filtering (scan #18), Top right: FNAL scan after filtering with MATLAB, Bottom left: filtered FNAL scan – reconverted into the NiobScan format, Bottom right: filtered DESY scan (see Figure 4).

4 DISCUSSION

Eddy current scans of the DESY calibration sheet indicate that the minimum sub-surface defect that the SNS eddy current scanner can resolve with close to 100% probability is ~120 microns. Since the defects in the DESY calibration disc were holes or Ta inclusions this statement refers to a very likely type of defect. It is not clear whether the eddy current response to the defects in the DESY calibration sheet is more the result of a difference in density (or even a hole!) or the result of the small difference in resistivity of Ta and Nb. Most likely the eddy current signal is of the former type. Magnetic steel inclusions, for instance, produce a signal that is larger than Ta and it is therefore believed that even smaller defects of this type can be resolved. It was furthermore shown above that bandpass filtering can even further improve the scanner resolution. Fig. 3 shows the result of a calculation using a simple model that describes the limiting magnetic surface field in a cavity as a function of the size of localized defect[4]. This very simple model, represented with Eq. 1, assumes that a spherical normal conducting inclusion of diameter *d* causes the quench of a cavity when as a result of the balance between heat generated by the RF magnetic field ($1/2R_nH^2$) in the normal conducting volume and the heat conducted away through the surrounding Nb ($\kappa\Delta T$) the defect reaches the critical temperature of the Nb (9.2 K) and thus causes the surrounding Nb to quench. This very simple model can only be used to obtain a ballpark estimate of the performance limit that is consistent with the limitation of the eddy current scanner resolution. **Figure 10** shows the result of a calculation using Eq. 1 with an assumed thermal conductivity of Nb of $\kappa \sim 50\ W/K/m$, a normal state surface resistance of $R_n \sim 1.5\ m\Omega$ and $C \sim 4\ mT/(MV/m)$. As can be seen from the curve in **Figure 10** the 120 micron detection limit of the scanner corresponds to a performance limit of ~25 MV/m in a TESLA type accelerating mode cavity.

$$E_{\max} = \frac{1}{C} B_{\max} = \frac{\mu_0}{C} H_{\max} = \frac{\mu_0}{C}\sqrt{\frac{4\kappa\left(T_c - T_b\right)}{d\, R_n}} \qquad \left(\frac{MV}{m}\right) \tag{1}$$

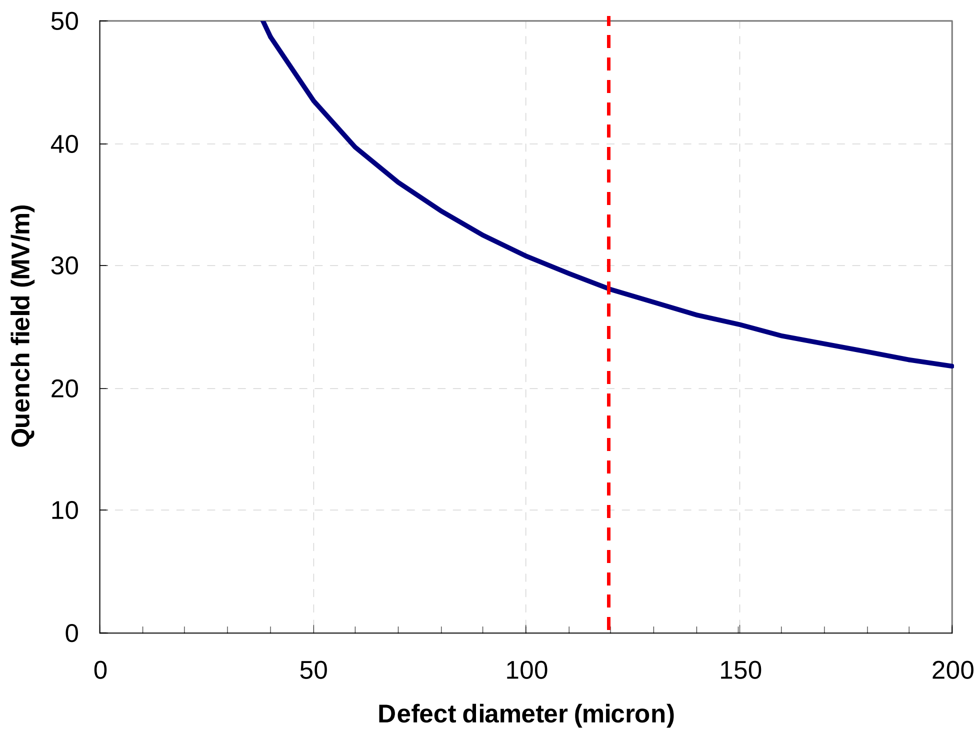


Figure 10: Average accelerating field gradient at which a thermal quench occurs in a TESLA type bulk-Nb cavity as a result of local heating in a spherical normal-conducting defect of a given diameter.

5 CONCLUSIONS

Testing of the DESY calibration sheet with the SNS scanner at Fermilab has shown that the scanner can resolve reliably 120 μm size subsurface Ta clusters and cracks/holes. This is especially true if data bandpass filtering is used. Variations of the turntable rotational speed and probe air-pressure did not yield any significant improvement of the scanner resolution. That means that the scanner is robust against day-to-day variations of for instance probe pressure. It was also found that the scanner resolution was not affected by a reduction of measurement points from the maximum setting. This is related to the fact that the scanner resolution is actually limited by the number of pixels on a screen or the printer dpi value. This limitation, however, is consistent with the 100 μm order resolution found. The number of points can therefore be reduced enough to reduce measurement time and speed up the filtering. The 1600 pts/track and the 100 microns track spacing was found to be a reasonable choice.

6 REFERENCES

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[2] P. Bauer, C. Boffo, L. Elementi, K. Ewald, "Eddy Current Scanner Operating Instructions", Fermilab, Technical division, Internal note TD-04-029, Aug. 2004

[3] C. Boffo, internal memo on bandpass filtering of eddy current scans

[4] H. Padamsee, RF Superconductivity for Accelerators, p. 206, Wiley&Sons, 1998;

APPENDIX A

Drawing of new pulley for ECS turntable.